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Applications of light-emitting diodes in researches conducted in aquatic environment

Naichia Yeh [a], Pulin Yeh [b], Naichien Shih [c], Omkar Byadgi [d], Ta Chih Cheng [d,*]

[a] *Center of General Education, MingDao University, 369 Wen-Hua Road, Peetou, Changhua 52345, Taiwan, ROC*
[b] *Department of Information Management, St. John's University, 499, Sec. 4, Tam King Road, Tamsui District, New Taipei City 25135, Taiwan, ROC*
[c] *Department of Electro-optical and Energy Engineering., Mingdao University, Taiwan*
[d] *Department of Tropical Agriculture and International Cooperation, National Pingtung University of Science and Technology, 1 Hseuh-Fu Road, Nei-Pu Hsiang, Pingtung 91201, Taiwan, ROC*

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ABSTRACT

With their good energy efficiency and characteristics that allow the adjustment of light intensity and spectral composition, light emitting diodes (LEDs) have opened up new research prospects for nutrition supply, pollution control as well as energy conversion and conservation. The potentials of LED as an effective light source for studies conducted in aquatic environment such as disinfection, fish behavior, biomass production, and photocatalyst activation have been explored to a greater extent since 1980's. As the third paper of a series that reviews LEDs' applications in scientific researches, this work concentrates in the researches on red, yellow, green, blue, and ultraviolet LEDs' applications published since mid-1990. The review is composed to demonstrate that LEDs are well qualified to succeed its more energy demanding counterparts in the research performed in aquatic environment. In addition, the authors have compiled a table that includes the findings covered in their previous works, which list some common types of LEDs and their respective usages in scientific researches.

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1. Introduction

LEDs are the first light source to make available the true spectral composition control. They permit the modification of

* Corresponding author. Tel.: +886 8 7703202x6423; fax: +886 8 7740446.
E-mail address: cheng.tachih@gmail.com (T. Chih Cheng).

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light intensity and wavelength to match the medical treatment requirements [1]. They can also match to plant photoreceptors to optimize production, as well as to influence plant morphology [2]. As such, the use of LEDs marks great improvements over existing indoor agricultural lighting. Also, LEDs have become the new favorite, following laser and intense pulsed light, in medical treatment and phototherapy.

In addition to a brief development history of LEDs, the previous reviews [1,2] of the researches that use LEDs for indoor plant cultivation and biomedical applications have indicated that the effective wavelengths are centralized in red, blue, and infrared segments for agricultural productions and medical treatments. These reviews have also suggested that the researches about the use of other wavelengths would lead to additional discoveries. To mend the gap that has been left behind from these reviews and to further demonstrate the versatility of LEDs, this paper inspects some researches that use yellow and green light LEDs and examines literatures in the areas of fishery, environmental, biomass productivity, and animal behavior adjustment.

2. Environmental applications

Ultraviolet light (UV) has become a growing alternative to chemicals in drinking water disinfection since UV inactivates chlorine resistant pathogenic organisms without producing known hazardous by-products [3,4]. Mercury lamps have been the primary source of UV radiations for conventional water purification as well as wastewater treatment. Low pressure mercury lamps emit nearly monochromatic UV light at a wavelength of 254 nm [5]. However, besides hazardous mercury contents, mercury vapor lamps are bulky; low shock resistant; energy consuming; and short lived ($\sim$4000–10,000 h). Using UV LEDs to perform the same function can eliminate all these disadvantages.

2.1. Disinfection

In addition to causing oxidation and other damages to DNA molecules via preventing their replication and transformation, UV activates the production of reactive intermediates such as hydroxyl radicals from water and organic matters. These radicals oxidize membrane and proteins of microorganisms as well as chemical pollutants such as pesticides [6], endocrine disruptors [7], and polycyclic aromatic hydrocarbons [8]. DNA absorbs UV between 200 and 300 nm [9], with a peak absorption (dependent on the target organisms) around 260–265 nm, which is the most effective germicidal range [10]. At higher wavelength range of 270–280 nm, DNAs' UV curve still displays significant absorption. It is, therefore, safe to say that the wavelengths of reasonable UV sources for water disinfection are between 240 and 280 nm.

Bowker et al. [11] have conducted a research to determine the UV fluence-response of three non-pathogenic microorganisms (*i.e.*, *MS*-2 *coliphage*, *T7 coliphage*, and *Escherichia coli*). They have compared the microbial UV dose responses under 255 and 275 nm LEDs and that under 254 nm low-pressure mercury lamps. The results indicate that (1) the mercury lamps have better *E. coli* and MS-2 inactivation efficiency than the LEDs of both wavelengths, (2) the 275 nm LEDs and the mercury lamps have similar T7 inactivation efficiency, (3) LEDs of the two wavelengths have similar microbial inactivation efficiency on MS-2, and (4) the 275 nm LEDs are more efficient on T7 and *E. coli* than the 255 nm ones. This study indicates that LEDs are suitable for UV disinfection although their low power output makes long exposure times necessary to induce significant results, UV LEDs are appropriate for point-of-use, low flow disinfection applications until their higher power output versions become available.

Würtele et al. [12] have investigated the suitability of GaN-based UV LEDs for water disinfection and concluded that these LEDs provide a promising alternative for decentralized and mobile water disinfection systems. After evaluating the performance characteristics of the LEDs under various water treatment requirements, these researchers designed a module with LEDs of 269 nm and 282 nm and use it with *Bacillus subtilis* spores for bioanalytical testing. The results indicate that UV LEDs effectively inactivate the test organism during both static and flow-through tests in varying water qualities. First flow-through tests demonstrated a linear correlation between inactivation and fluence. For the same fluence, the 269 nm LEDs attained a higher inactivation level than their 282 nm counterparts. The study also shows that the 282 nm LEDs' higher photon flux tends to compensate their lower inactivation level.

Chevremont et al. [13] have investigated the efficiency of UV-A (315–400 nm) and UV-C (100–280 nm) LEDs on bacteria inactivation using bioindicators of fecal pollution in wastewaters. Among four parameters (*i.e.*, pH, bacterial density, exposure time, and wavelength) tested on simple bacterial cultures, the wavelength and the exposure time factors tend to trigger more significant responses. The combined wavelengths of 280/365 nm and 280/405 nm have the best bactericidal effect. No bacterial reactivation has been identified after 60 s of exposure. In another experiment [14], this group of researchers have studied the efficiency of UV-A and UV-C radiations on bacterial and chemical indicators. Through monitoring the endurance of fecal bioindicators in wastewaters as well as the oxidation of conventional organic matter and the aromatic pollutant, they have found that combining UV-A and UV-C results in better microbial reduction comparing to a single bandwidth. The combination of the two oxidizes up to 37% of creatinines and phenols. Such efficiency is comparable to what achievable with the use of photocatalyst like anatase titanium dioxide (TiO_2). A more recent study of photoactivated disinfection (PAD) using LED [15] has shown a reduction of the microbe colony-forming unit (CFU) counts in saline by 1.42 $\log_{10}$ after 30 s and by 1.99 $\log_{10}$ after 60 s compared with negative controls.

2.2. Photocatalyst activation

Fujishima and Honda [16] discovered the photocatalytic activity of TiO_2 when they used UV to irradiate TiO_2 electrode to split H_2O for H_2. With a 3.2 eV band gap, TiO_2 can generate electron–hole (e^-–h^+) pairs and become a highly active photocatalyst when irradiated with UV. The e^- (a strong reducing agent) in conductive band can react with O_2 to produce O^{2-} ($O_2+4e^- \rightarrow 2O^{2-}$). The h^+ (a strong oxidizing agent) in valence band can pull the charges from H_2O to produce OH^- ($2H_2O \rightarrow 2OH^- + H_2 + 2h^+$). These free radical species can attack organic molecules via radical addition, hydrogen abstraction, or electron transfer [17] and thereby efficiently degrade organic materials [18]. H_2O_2 is also generated during the photocatalytic process [19,20]. UV LEDs in combination with H_2O_2 are promising for wastewater treatment via photodegradation of aqueous phenols and other organic compounds [21]. Researches in the field of TiO_2 applications using UV have been abundant [22–26] as UV is able to match the 3.2 eV band gap of TiO_2. Considering UV's hazard to the human eyes, however, strategies have been developed to adapt TiO_2 to visible light.

Cheng et al. [27] have used blue LED activated TiO_2/Fe_3O_4 particles to evaluate the photocatalytic activity efficiency of the particles. The result indicates that blue LED is a feasible light source to activate the photocatalytic effects of TiO_2/Fe_3O_4 in both freshwater and seawater. The particles activated by the energy-saving blue LEDs are fully capable of disinfecting marine fish pathogen in seawater. Compared to UV, blue LED has the advantage of the same effect with less harm to human eyes. Lu et al. [28] have shown that TiO_2/magnetic Fe_3O_4/floating fly-ash cenospheres

photocatalyst exhibits a high catalytic efficiency and excellent photochemical stability. Their experiment demonstrate a 75.32% removal efficiency for enrofloxacin hydrochloride residue degradation under visible light after 60 min.

2.3. Sensing device

LEDs, due to their small size, can be readily integrated with microchip as an excitation source [29] and therefore have attracted a significant attention in the analytical field [30]. Among works on LED applications in this field; Yao et al. [31] have developed a microfluidic device that integrates a green organic LED and a thin film interference filter into a single chip for proteins fluorescence detection; Su and Lin [32] have developed a method to analyze riboflavin in urine with LED-induced fluorescence detection and capillary electrophoresis; and Křcova´ et al. [33] have described a device using UV-LED for photometric detection in a capillary electrophoresis.

The detection device for ammonia (NH_3), an important micronutrient and intermediate of the nitrogen cycle in the aquatic systems, has become of interest to environmental pollution control industry. Ammonia can cut the growth or reproductive capability of aquatic organisms. High concentration of NH_3 can cause nutrient enrichment in water ecosystem and thereby depletes oxygen, sets off toxicity, and brings about human health hazard. Ammonia is also an atmospheric base that causes alkaline pollutant in freshwater [34]. The US and the European Union are among the countries that routinely monitor NH_3·s in their wastewater. Japan also monitors the ammonia contents in their drinking water [35].

Xue et al. [36] have developed a microfluidic device integrated with a fluorescence detection system for detecting ammonia in aqueous samples. They mounted a 365-nm UV LED, an excitation source, with a band filter on a microchip. With the presence of a reducing reagent, Na_2SO_3, the ammonia sample can react with o-phthaldialdehyde (OPA) on-chip. This sample can produce a fluorescent isoindole derivative that emits 425 nm fluorescence signals when excited with the UV LED. This device can detect NH_3 levels in precipitations and water bodies as well as being used to detect of other analytes via fluorescence.

Food crisis arisen from mad cow disease, foot-and-mouth disease, and chicken flu virus has brought about global food safety concerns. Such concerns consequently raise the fishery industry's interest in developing fast, accurate, reliable, objective, cost-effective, and non-destructive methods to evaluate real-time freshness of seafood products. Approaches for determining fish quality include sensory (odor, taste, texture), physical (texture, electrical properties), chemical (lipid oxidation, total volatile basic nitrogen or TVB-N) and microbiological (total viable count or TVC) [37].

Pacquit et al. [38] have demonstrated an on-package sensor for real-time monitoring of fish freshness. The sensor contains bromocresol green, a pH-sensitive dye that responds to basic volatile spoilage compounds via color change. The dye's maximum absorption wavelength shifts from 438 nm to 615 nm when the pH of the dye turns from acidic to basic. This color change is monitored with a reflectance colorimeter based on a photodetector and yellow LEDs (590 nm), which have good spectral overlap with the absorbance spectrum of the dye's basic form. The studies of the sensor's characteristics and its response with standard ammonia gas have verified that the sensor response correlates with bacterial growth patterns in fish samples. This result has made feasible for real-time monitoring of spoilage in various fish species.

3. Biomass production

Algae capable of producing high starch/cellulose can be a great alternative to food crops for bioethanol production without compromising food supplies, rainforests, or arable land [39]. Microalgae have become one of the global research focuses thanks to their ability to produce an intracellular lipid feedstock suitable for biodiesel conversion [40–42].

An effectively integrated algal system can minimize the negative effects of CO_2 and water pollution while providing useful chemicals to drive down the costs of green fuels [43]. Along with the oxygen generated in the photoautotrophic conditions, microalgae produce various value-added by-products. Some microalgal species are able to accumulate 50–70% of oil/lipid per dry weight and can produce more oil per hectare than any other energy crop. Thus, microalgae have been recognized as an important material for biofuels [44]. Due to algae's huge genetic diversit, however, improving algal biomass productivity with cost-effective processes is still tricky. As cost-effective technologies that would allow efficient biomass harvesting and oil extraction are yet to be developed, intense research in harnessing algae and their industrial wastes to produce environmentally friendly fuel is expected [45].

3.1. Algal cultivation

This section assesses the microalgae cultivation literatures that involve the use of green and yellow lights LEDs, which are rarely used in the indoor plant cultivation since red and blue lights are much better sources that drive photosynthetic metabolism [2].

Spirulina platensis (a blue-green microalgae with high proteins, carotene, vitamins, phycocyanin and linolenic acid) is often used as a sample species to investigate microalgae's growth patterns, photosynthesis pigment contents, and light pattern responses [46–48]. Chen et al. [49] have studied red, yellow, green, blue, and white LEDs of various intensities to investigate the growth of *S. platensis* and the effects of light sources on its *chlorophyll a* (*Chl*) and *phycocyanin* (*Phy*) production. They have found that (1) red light is the best for algae growth, (2) yellow light gives the best specific *Chl* production rate with a light intensity of 750 or 1500 $\mu mol/m^2 s$, (3) blue light yields the best specific pigments (for both *Chl* and *Phy*) production rates at 3000 $\mu mol/m^2 s$, and (4) neither green nor white LEDs make the performance list in this experiment.

The unsatisfactory performance of green light is expectable because chlorophyll reflects instead of absorbing green light. As for white LEDs, different spectra may appear white due to metamerism. There are several ways to fabricate LEDs that generate white light. One is to mix the light from individual red, green, and blue LEDs to form white light. Another one is to convert the light from monochromatic UV or blue LED to white light using phosphor materials [50]. It is possible that the white LEDs used in their experiment does not contain the right light quality to perform. Researchers who wish to conduct experiments using white LEDs in the future should make a note of this.

The results of another *S. platensis* study [51] under LEDs of various wavelengths and illuminations confirmed that red light is the most effective light source for the species' photoautotrophic cultivation. Blue LEDs yield the lowest biomass due to the absence of blue absorption bands in chlorophyll. As there is no need to direct energy to the less efficient segments, using narrow bands red LEDs instead of fluorescent lamps to drive the photosynthesis of blue-green microalgae in artificial environments constitutes a good energy saving practice. Nevertheless, further investigation is worthwhile since using LEDs of different spectrum segments for photosynthesis may trigger different biochemical processes of values.

Das et al. [52] have studied biomass productivity and fatty acid methyl esters (FAME) derived from intracellular lipid of *Nannochloropsis sp*. They grew *Nannochloropsis sp*. in both phototrophic and mixotrophic culture conditions under red, green, blue, and white LEDs of various intensities. The magnitude of maximum

specific growth rates as recorded are observed, in descending order, under blue, white, green, and red LEDs. While the maximum volumetric FAME yield is achieved in the cultures exposed to blue LED due to the highest biomass productivity, the maximum FAME yield occurs in the cultures exposed to green LEDs. For a given light intensity, incremental exposure of light over the cell growth cycle saves energy by about 20% relative to continuous illumination. Red lights play a more important role than green lights in photosynthesis since green plants reflect, rather than absorbing, mostly green and near-green light. However, *Nannochloropsis* is different from chlorophyll-based microalgae since it lacks chlorophyll b and chlorophyll c. *Nannochloropsis'* capability to build a high concentration of carotenoid pigments that include astaxanthin, zeaxanthin, and canthaxanthin might be the reason why green LEDs outperformed the red ones in this case. Koc et al. [53] have used red LEDs, blue LEDs, and fluorescent lights respectively in the photobioreactors to grow *Chlorella kessleri* for oil content improvement in algae. Results have indicated that red LED produces the highest number of cells with the highest weight.

3.2. Bacteria cultivation

Photosynthetic bacteria (PSB) contain carotenoids, bacteriochlorophylls, and other photosynthetic pigments. These pigments help PSB to convert light into chemical energy via anoxygenic photosynthesis and grow autotrophically with CO_2 as the carbon source [54]. PSB, provide prey organisms and serve as diet ingredients, have been widely used in aquaculture production as probiotics because they act as a disease-prevention agent. *Rhodopseudomonas palustris* (*R. palustris*) is a phototrophic PSB bacterium that can modulate its photosynthesis in accordance with the amount of light available. *R. palustris* responds to low light environment by increasing the level of light-harvesting complexes for light absorption [55].

Kuo et al. [56] have investigated the effects of eight light sources on *R. palustris* growth and carotenoid content with dark condition as the control. The specimen were cultured for 144 h under the ~2000 l× light sources that include incandescent lamp, halogen lamp, fluorescence lamp, and LEDs of white, yellow, red, blue, and green lights. The results indicate that blue LEDs are the best for the growth, the carotenoids contents, and the productivity of *R. palustris*. The blue LED is most energy efficient as it saves 75% energy, compared with incandescent lamp, while increasing carotenoids productivity by 348%. Yellow LEDs outperform all other light sources, except for blue LED, in carotenoids productivity. *R. palustris* grows significantly slower in the dark than under illumination. Except for the green LEDs, which do not contribute any more growth than the dark condition, LEDs generally have higher energy efficiency for bacterial growth than conventional light sources.

Combining LED illuminations of various wavelengths may result in the finding of the highest species-specific absorption spectrum and the optimal approaches to maximize cultivating

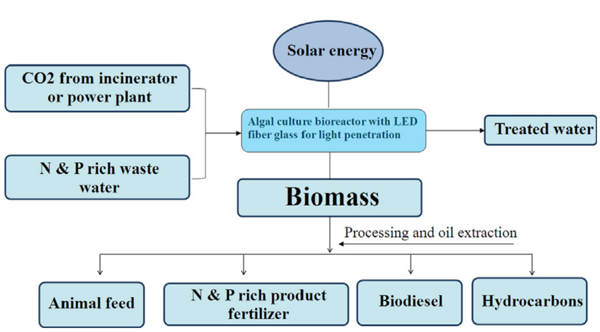

Fig. 1. Concept of integrated bioremediation with microalgae applications.

efficiency for a given species. A study conducted by Katsuda et al. [57] has made a good example of this. In that study, red LEDs are used first to enhance the cell growth of *H. pluvialis* and then the light source is switched to shorter wavelength (380–470 nm) for astaxanthin production improvement.

3.3. Pollution control via biomass production

Plants, microbes, and algae absorb nitrogen from air, soil, or water and store it as biomass. Over time the decomposed biomass releases the nitrogen back to the environment. Nitrogen is essential for a healthy ecosystem, if in excess, however, it causes toxic algal blooms, exhausts oxygen, and evades biodiversity [58]. Less than 20% of water-soluble phosphate in fertilizer is absorbed by plants [59]. The rest seeps through soils, ends up in groundwater or surface water bodies [60], and causes water pollution.

Nitrogen and phosphorous, while being serious pollutants in some water bodies, are key nutrients to algae. Therefore, algae can thrive in nitrogen- and phosphorus-rich wastewaters [61]. Algae remove nitrogen and phosphorus from their environment and thus decrease the nutrient levels and improve water quality [62]. Capturing these nutrients to use as fertilizer provides an added value to biomass.

Together with light and carbon, nitrogen and phosphorous are the most important inputs for biofuel production. Light penetration may be difficult due to the dense algal cultures and is the main limiting factor for algal productions both in field and bioreactor. While green light is the least favorable wavelength in plant cultivation, its penetration depth is 20 times over that of blue and red lights [63]. As such, the study of better use of green light in dense algal cultures is an interesting research direction. Fig. 1 demonstrates a concept that integrates bioremediation with biofuel creation. This concept features nitrogen and phosphorus capturing and retrieval with benefits of water treatment and algae production.

4. Fishery

Light is an environmental factor with characteristics that deeply affect the physiology of fish [64]. These characteristics include quality (wavelength), quantity (intensity), and periodicity (photoperiod). LEDs have become popular in aquaculture industry that include fish farming because they have narrow bandwidth outputs and permit intensity and spectrum manipulation to simulate the environmental conditions that match the target species' sensitivities [65,66]. Light attenuates with increasing depth and the spectral composition of light changes differentially underwater. While the long end of visible spectrum penetrates relatively shallow waters, the short end becomes predominant in deeper area.

4.1. Fish behavior

Fish, with the responsiveness to light differ from species to species [67], can detect light intensity and spectrum changes by retinal and extra-retinal photoreceptors [68,69]. As a result, defining optimum photo conditions based on species is necessary when supporting the development of fish and inducing fish reproduction in artificial environment. Metal halide lights used as standard in commercial Atlantic salmon sea cages to enhance productivity may create spotted bright lights that could compromise fish welfare. With an intention to study the feasibility of replacing metal halide lights, researchers have been investigating to see if LEDs would cause potential adverse effects in fish. Migaud et al. [70] have conducted a study in post-smolt Atlantic salmon, *Salmo salar*, to determine the effect of increasing intensities of blue LED light on the fish light perception and stress response and to

examine their potential retinal damage under these conditions. Their results demonstrate that salmon perceives blue LED light at 0.1 m from the light source between the intensity of 0.199 W/m^2 and 2.7 W/m^2, and that salmon exposed to high intensity blue LED light shows an increase in plasma cortisol and glucose levels within 3 h. Further, 24 h after the lights are on, these levels returns to a basal state, which indicates that the fish has adapted to the stress event following the initial stress response [71]. However, the fish exposed to the white LED and lower blue light intensities shows no such acute stress response.

Fishing lamps are key components for squid luring and catching. The light sources of fishing lamps have evolved from torch, acetylene, incandescent, mercury, fluorescent, and halogen lamps to the current metal halide lamps [72]. Increasing fishing light illumination, while increases deep fishing, increases the cost of fuel and related equipment. To reduce the cost, some researchers have looked into the behavior of squid in response to lights of different sources [73,74]. Researches that review LEDs' illuminating characteristics as the potential fishing lamps and report their prospects for being developed as fishing lamps are abundant. These researches include the study of the relationship between underwater irradiance and distribution of squid under fishing lights [75], radiation and underwater transmission characteristics of LED fishing lamps [76], and squid catching efficiency along with squids' reaction to LEDs of different colors [77] and to the shadow section of LEDs [78].

In order to identify the appropriate wavelength for fishing light and decide which LED is more effective on squid fishing and catching, Jeong et al. [79] have studied the retinular responses and the light adaptation conditions of common squid (*Todarodes pacificus*) to blue, red, and white LEDs in the water tank. Their results, although have not demonstrated the most ideal wavelength for fish catching, indicate that the blue light is an excellent luring source because the retina of squid is highly sensitive to blue wavelength. The results of their lab experiment and field test show that the blue LEDs are useful for squid gathering and the white LEDs, which induces good light adaptation, are useful for squid fishing. Combination of these two sources is desirable for combining results of satisfactory gathering and fishing. Application of LEDs that can efficiently emit monochromatic light is expected to bring enormous energy savings. Using blue LED, which has outstanding transmission characteristic in the sea, helps to save over 90% of energy according to this research.

Matsushita et al. [80] have monitored fuel consumption of coastal squid jigging boats. The observation has indicated, with all lamps turned on, the average fuel consumption for boats over 16 gross tons (GT) and equipped with 53 metal halide lamps (MHs, with ~150 kW total output) is 54–63 *l*/h per boat. When LED modules are in place of 23 MHs (*i.e.*, when the boat is equipped with LED modules and 30 MHs) to drop the total lighting output to 99 kW, fuel consumption drops 31% to an average of 42.3 l/h per boat. When uses only LEDs (6.48 and 9.00 kW total output, respectively), fuel consumption drops further to 22.4 and 25.5 l/h, respectively. This research shows that applying low-energy LEDs in the squid jigging fishery help to save fuels as well.

4.2. Fish production

Migaud et al. [81] have investigated spectral effects on Atlantic cod performances using blue, green, red, and white (peaks at 460 nm and 560 nm) LEDs. The study shows that the larvae reared under narrow bandwidth blue (455 nm) and green (530 nm) lights or white light with high proportion of shorter wavelength develope 75%–80% more dry weight than those under red lights. This finding matches up with Downing and Litvak's [82], in which haddock (*M. aeglefinus*) raised under blue light (470 nm) feed more actively and capture more prey at the start of exogenous feeding.

Via investigating the effects of LED irradiance and light spectrum on the growth of a model scleractinian coral species, *Galaxea fascicularis*, Wijgerde et al. [83] have demonstrated that LED can be a suitable light source for coral aquaculture. The study indicates that the light skewed towards blue segment results in high coral growth.

4.3. Fish reproduction

Photoperiod can regulate reproductive activities in seasonal breeders. Bromage et al. [84] have used long and short photoperiodic conditions in aquaculture to manipulate reproduction activities in certain fish to prove the influence of photoperiod to fish reproduction behavior. The sapphire devil (*Chrysiptera cyanea*, a reef-associated damselfish) is a useful model for the researches about the effect of light characteristics on the reproductive activity of reef fish. Bapary et al. [85] have reported that the reproductive performance of this species exhibits photoperiodism. Under long-day conditions (light to dark ratio of LD = 14:10), vitellogenesis is induced in the sapphire devil in the non-reproductive season and in the ophthalmectomized fish [86]. In a latter experiment that examines the wavelength involvement in the ovarian development of sapphire devil, Bapary et al. [87] have reared ten fish in each group under long photoperiod using red, green, blue, and white LEDs; with the fish reared in natural light as control. This 45-day experiment during the fish's non-reproduction season has demonstrated that the ovarian maturation occurs in fish exposed to red (627 nm), green (530 nm), and blue (455 nm) lights, but not to fish under white or natural lights. The results demonstrate that long days are stimulatory to sapphire devil reproduction and that wavelength of light influences sapphire devil's gonad maturation, with the influence level of red > green > blue. Such level of influence suggests that the activating spectrum is distributed in longer wavelength. A red-light-sensitive opsin is functionally expressed in the deep brain to stimulate the photoperiodic ovarian development in the fish. As shallow reefs are rich in long wavelength, the effectiveness of long wavelength may be attributed to sapphire devil's adaptation to the natural photic environments. To confirm the effectiveness of red light on the initiation of ovarian development, Takeuchi et al. [88] have conducted a study exposing the sapphire devil to long-day condition (LD = 14:10) created with red light LED (627 nm). They have observed the appearance of vitellogenic oocytes in ovaries within one week. This result suggests that the fish immediately undergo oocyte development under red wavelength and that red-light-sensitive cone opsin may be a candidate of deep brain photoreceptor molecule involved in the fish's photoperiodic ovarian development. In shrimp culture, Mueangdee et al. [89] have made a LED containing pipe fixed inside the broodstock tank of *Penaeus monodon* to detect the spawning. The device has been able to detect egg releasing as early as 22 s after the onset of spawning.

5. Conclusion

The researches reviewed in this paper indicate that LEDs have become light source of great popularity for the studies in aquatic environment. Using narrow band LEDs to rule out non-productive spectrum from the wavelength-specific applications can be a desirable production-enhancing and energy-saving practice.

Table 1, which includes the findings covered within the previous work by Yeh et al. [1,2], lists some common types of LEDs and their respective uses in scientific researches. While the LEDs in red, blue, and infrared segments are more effective for both agricultural production and medical treatment, green and yellow LEDs have found their uses in aquaculture investigation. The uses of orange LEDs for scientific researches, however, are relatively

Table 1
Some common types of LEDs and their potential for agriculture, medical, and environmental uses.

LED color	Peak wavelength (nm)	Material and structure	Substrate	Suitable for
Infrared	> 760	GaAs, AlGaAs	–	Oral mucositis prevention and management (880 mm) [90]
Far red/near infrared	730	GaAs	GaP	Microalgae carotenoid accumulation [91]
				Low level light therapy (630–1000 mm) [92]
Red	700	GaP:Zn-O		Plant morphology, tissue culture and growth [93]
				Plant seedling, space agriculture [94]
				Wound healing, mucositis prevention, and tissue repair [95,96]
	~660	$GaAl_{0.35}As_{0.65}$	GaAs	Algal culture [97,98]
	~650	$GaAs_{0.6}P_{0.4}$		Allergic rhinitis treatment [99]
				Embryo development, egg hatching rate improvement [100]
				Incision and wound healing, [101]
				Plant photo morphogenesis, plant tissue culture and growth [93]
				Plantlet morphology control in micro propagation [102]
Orange-red	~ 630	$GaAs_{0.35}P_{0.65}$:N	GaP	Acne treatment [103]
				Biomass production (algae growth, microalgae cultivation) [104]
				Plant tissue culture and growth [105]
				Wound healing, anti-inflammatory [106],
Orange	~610	$GaAs_{0.25}P_{0.75}$:N	GaP	Photodetector for pesticide detection [107]
Yellow-orange	590–610	AlGaInP		Sensors for fish spoilage monitoring [38]
Yellow	~590	$GaAs_{0.15}P_{0.85}$:N	GaP	Algae growth, non-chlorophyll photosynthesis pigment production [49]
	~585	$GaAs_{0.14}$ $P_{0.86}$:N	GaAs	Bacteria cultivation [55]
	570–590	GaAsP, AlGaInP	GaP	Fish spoilage monitoring [38]
Green	~565	GaP:N	GaP	Biomass production (bacteria cultivation, microalgae cultivation) [55]
				Biomass production (algae growth) [45]
	530–555	AlGaInN	GaN	Fishery, fish behavior [108]
	500–570	InGaN, AlGaInP, AlGaP		
Blue	450–500	ZnSe, InGaN	SiC	Biomass production (algae growth, astaxanthin production)[109,110]
	~450	GaN		Dental composite polymerization [111–113]
				Fishery, fish behavior [77]
				Newborn jaundice treatment [114]
				Photocatalyst activation [27]
				Plant disease control [115]
				Plant tissue culture and growth [93]
				Rheumatoid arthritis treatment [116]
Ultraviolet	~400	AlGaN	AlN	Acne treatment [117]
	250–290	GaN	–	Dermatological researches [118–121]
	210–400	AlGaInN	Diamond	Disinfection, water treatment and purification [11–14]

rare. Nevertheless, developing sensing device for detecting chemicals or dyes that have absorbance spectrum in the range of 590–620 nm marks a good start.

The following conclusions can also be drawn from the table:

- LEDs in the infrared and ultraviolet range are the dominant light sources used in the biomedical studies.
- LEDs in the red and near infrared range generate the most favorable results for indoor planting.
- LEDs in the yellow and green range are the most common light sources used in the aquaculture applications such as fish behavior study and algae-based biomass production.
- Red LEDs are the predominant light sources used in the agriculture researches.
- Ultraviolet LEDs are the prevailing light sources used in biomedical researches and environmental disinfections.
- Blue LEDs, the most versatile light sources, are suitable for all areas listed in Table 1.

The characteristics of LEDs that allow light intensity adjustment and spectral composition control are unmatchable by the conventional light sources. Therefore, it is not risky to say that LEDs have set their positions to replace most of these sources in the field of scientific research.

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References

[1] Yeh N, Wu CH, Cheng TC. Light-emitting diodes – their potential in biomedical applications. Renew Sustain Energy 2010;14:2161–6.
[2] Yeh N, Chung J-P. High-brightness LEDs – energy efficient lighting sources and their potential in indoor plant cultivation. Renew Sustain Energy 2009;13:2175–80.
[3] Liberti L, Notarnicola M, Petruzzelli D. Advanced treatment for municipal wastewater reuse in agriculture. UV disinfection: parasite removal and by-product formation. Desalination 2002;152(Feb):315–24.
[4] Bohrerova Z, Shemer H, Lantis R, Impellitteri CA, Linden KG. Comparative disinfection efficiency of pulse and continuous-wave UV irradiation technologies. Water Res 2008;42(Jun):2975–82.
[5] Bolton JR, Cotton CA. The Ultraviolet Disinfection Handbook. Denver, CO, USA: American Water Works Association; 2008.
[6] Chen PJ, Rosenfeld EJ, Kullman SW, Hinton DE, Linden KG. Biological assessments of a mixture of endocrine disruptors at environmentally relevant concentrations in water following UV/H_2O_2 oxidation. Sci Total Environ 2007;376(April):18–26.
[7] Woo OT, Chung WK, Wong KH, Chow AT, Wong PK. Photocatalytic oxidation of polycyclic aromatic hydrocarbons: intermediates identification and toxicity testing. J Hazard Mater 2009;168(Sep):1192–9.
[8] Badawy MI, Ghaly MY, Gad-Allah TA. Advanced oxidation processes for the removal of organo-phosphorus pesticides from wastewater. Desalination 2006;194(Jun):166–75.
[9] Chen RZ, Craik SA, Bolton JR. Comparison of the action spectra and relative DNA absorbance spectra of microorganisms: information important for the determination of germicidal fluence (UV dose) in an ultraviolet disinfection of water. Water Res 2009;43(Dec):5087–96.
[10] Kalisvaart BF. Re-use of wastewater: preventing the recovery of pathogens by using medium-pressure UV lamp technology. Water Sci Technol 2004;50(6):337–44.
[11] Bowker C, Sain A, Shatalov M, Ducoste J. Microbial UV fluence-response assessment using a novel UV-LED collimated beam system. Water Res 2011;45(Feb):2011–9.
[12] Würtele MA, Kolbe T, Lipsz M, Kulberg A, Weyers M, Kneissl M, et al. Application of GaN-based ultraviolet-C light emitting diodes – UV LEDs – for water disinfection. Water Res 2011;45(Jan):1481–9.

[13] Chevremont AC, Farnet A, Sergent M, Coulomb B, Boudenne JL. Multivariate optimization of fecal bioindicator inactivation by coupling UV-A and UV-C LEDs. Desalination 2012;285(Jan):219–25.
[14] Chevremont AC, Farnet A, Coulomb B, Boudenne JL. Effect of coupled UV-A and UV-C LEDs on both microbiological and chemical pollution of urban wastewaters. Sci Total Environ 2012;426(Jun):304–10.
[15] Eick S, Markauskaite G, Nietzsche S, Laugisch O, Salvi GE, Sculean A. Effect of photoactivated disinfection with a light-emitting diode on bacterial species and biofilms associated with periodontitis and peri-implantitis. Photodiagn Photodyn Ther 2013.
[16] Fujishima A, Honda K. Electrochemical photolysis of water at a semiconductor electrode. Nature 1972;238:37–8.
[17] Tchobanoglous G, Burton FL, Burton F, Stensel HD Wastewater Engineering: Treatment and Reuse, 4th ed., Inc. Metcalf and Eddy, McGraw-Hill Companies Inc., NewYork, USA, 2005.
[18] Fujishima A, Rao TN, Tryk DA. Titanium dioxide photocatalysis. Photochem Photobiol C Photochem Rev 2000;1(Jun):1–21.
[19] Fox MA, Dulay MT. Heterogenous photocatalysis. Chem Rev 1993;93 (Jan):341–57.
[20] Okamoto K, Yasunori Y, Hirok T, Masashi T, Akira T. Heterogenous photocatalytic decomposition of phenol over TiO_2 powder. Bull Chem Soc Jpn 1985;58:2015–22.
[21] Vilhunen SH, Sillanpää MET. Ultraviolet light emitting diodes and hydrogen peroxide in the photodegradation of aqueous phenol. J Hazard Mater 2009;161(Jan):1530–4.
[22] Rodríguez-González V, Alfaro SO, Torres-Martínez LM, Cho SH, Lee SW. Silver–TiO_2 nanocomposites: synthesis and harmful algae bloom UV-photoelimination. Appl Catal B: Environ 2010;98(Aug):229–34.
[23] Zan L, Fa W, Peng T, Gong ZK. Photocatalysis effect of nanometer TiO_2 and TiO_2-coated ceramic plate on /hepatitis B virus. J Photochem Photobiol B Biol 2007;86:165–9.
[24] Khan U, Benabderrazik N, Bourdelais AJ, Baden DG, Rein K, Gardinali PR, et al. UV and solar TiO_2 photocatalysis of brevetoxins (PbTxs). Toxicon 2010;55 (May):1008–16.
[25] Luo L, Miao L, Tanemura S, Tanemura M. Photocatalytic sterilization of TiO_2 films coated on Al fiber. Mater Sci Eng B 2008;148(Feb):183–6.
[26] Cheng TC, Chang CY, Chang CI, Hwang CJ, Hsu HC, Wang DY, et al. Photocatalytic bactericidal effect of TiO_2 film on fish pathogens. Surf Coat Technol 2008;203(Dec):925–7.
[27] Cheng TC, Tao KS, Yeh N, Chang CI, Hsu HC, Gonzalez F, et al. Bactericidal effect of blue LED light irradiated TiO_2/Fe_3O_4 particles on fish pathogen in seawater. Thin Solid Films 2011;519(May):5002–6.
[28] Lu Z, Zhou W, Huo P, Luo Y, He M, Pan J, et al. Performance of a novel TiO_2 photocatalyst based on the magnetic floating flyash cenospheres for the purpose of treating waste by waste. Chem Eng J 2013;225:34–42.
[29] Novak L, Neuzil P, Pipper J, Zhang Y, Lee SH. An integrated fluorescence detection system for lab-on-a-chip applications. Lab Chip 2007;7 (Jan):27–9.
[30] de Jong EP, Lucy CA. Low-picomolar limits of detection using high-power light-emitting diodes for fluorescence. Analyst 2006;131(May):664–9.
[31] Yao B, Luo GA, Wang LD, Gao YD, Lei GT, Ren KN, et al. A microfluidic device using a green organic light emitting diode as an integrated excitation source. Lab Chip 2005;5(Oct):1041–7.
[32] Su AK, Lin CH. Determination of riboflavin in urine by capillary electrophoresis-blue light emitting diode-induced fluorescence detection combined with a stacking technique. J Chromatogr B 2003;785 (Feb):39–46.
[33] Kr̆cova´ L, Stjernlof A, Mehlen S, Hauser PC, Abele S, Paull B, et al. Deep – UV-LEDs in photometric detection: a 255 nm LED on-capillary detector in capillary electrophoresis. Analyst 2009;134(Dec):2394–6.
[34] Camargo JA, Alonso A. Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: a global assessment. Environ Int 2006;32(Aug):831–49.
[35] Gray SM, Ellis PS, Grace MR, McKelvie ID. Spectrophotometric determination of ammonia in estuarine waters by hybrid reagent-injection gas-diffusion flow analysis. Spectrosc Lett 2006;39(6):737–53.
[36] Xue S, Uchiyama K, Li HF. Determination of ammonium on an integrated microchip with LED-induced fluorescence detection. J Environ Sci 2012;24 (3):564–70.
[37] Olafsdottir G, Martinsdottir E, Oehlenschlager J, Dalgaard P, Jensen B, Undeland I, et al. Methods to evaluate fish freshness in research and industry. Trends Food Sci Technol 1997;8(8):258–65.
[38] Pacquit A, Lau KT, McLaughlin H, Frisby J, Quilty B, Diamond D. Development of a volatile amine sensor for the monitoring of fish spoilage. Talanta 2006;69(April):515–20.
[39] Subhadra B, Edwards M. An integrated renewable energy park approach for algal biofuel production in United States. Energy Policy 2010;38(Sep): 4897–4902.
[40] Pedroni P, Beckert H, Bergman P, Benemann J. In: Gale J, kaya Y, editors. International network for biofixation of CO_2 and greenhouse abatement with microalgae. Greenhouse Gas Control Technologies; 2003. p. 1863–6.
[41] Huntley ME, Redalje DG. CO_2 mitigation and renewable oil form photosynthetic microbes: a new appraisal. Mitig Adapt Strat Global Change 2007;12 (May):573–608.
[42] Singh A, Singh PN, Murphy JD. Renewable fuels from algae: an answer to debatable land based fuels. Bioresour Technol 2010;102(Jan):10–6.
[43] John RP, Anisha GS, Nampoothiri KM, Pandey A. Micro and macroalgal biomass: a renewable source for bioethanol. Bioresour Technol 2011;102 (Jan):186–93.
[44] Chisti Y. Biodiesel from microalgae. Biotechnol Adv 2007;25(Feb):294–306.
[45] Sivakumar G, Xu J, Thompson RW, Yang Y, Smit PR, Weathers J. Integrated green algal technology for bioremediation and biofuel. Bioresour Technol 2012;107(Mar):1–9.
[46] Hirata S, Taya M, Tone S. Continuous culture of *Spirulina platensis* under photoautotrophic conditions with change in light intensity. J Chem Eng Jpn 1998;31(4):636–9.
[47] Chojnacka K, Noworyta A. Evaluation of *Spirulina* sp. growth in photoautotrophic, heterotrophic and mixotrophic cultures. Enzyme Microb Technol 2004;34(April):461–5.
[48] Costa JAV, Colla LM, Filho PFD. Improving *Spirulina platensis* biomass yield using a fed-batch process. Bioresour Technol 2004;92(May):237–41.
[49] Chen CY, Yeh KL, Aisyah R, Lee DJ, Chang JS. Cultivation, photobioreactor design and harvesting of microalgae for biodiesel production: A critical review. Bioresour Technol 2011;102(Jan):71–81.
[50] Nakamura S., Fasol G., Pearton S.J. The blue laser diode: the complete story. 2nd ed. Springer; Santa Barbara, Tokyo, June, 2000; 20003-540-66505-6.
[51] Chen HB, Wu JY, Wang CF, Fu CC, Shieh CJ, Chen CI, et al. Modeling on chlorophyll a and phycocyanin production by *Spirulina platensis* under various light-emitting diodes. Biochem Eng J 2010;53(Dec):52–6.
[52] Das P, Lei W, Aziz AA, Obbard JP. Enhanced algae growth in both phototrophic and mixotrophic culture under blue light. Bioresour Technol 2011;102(Feb):3883–7.
[53] Koc C, Anderson GA, Kommareddy A. Use of red and blue light-emitting diodes (LED) and fluorescent lamps to grow microalgae in a photobioreactor. Isr J Aquac 2013;65(Oct):797–805.
[54] Pfennig N. *Rhodopseudomonas acidophila*, sp. n., a new species of the budding purple nonsulfur bacteria. J Bacteriol 1969;99(Aug):597–602.
[55] Imhoff JF. Taxonomy and physiology of phototrophic purple bacteria and green sulfur bacteria. In: Blankenship RE, Madigan MT, Bauer CE, editors. Anoxygenic Photosynthetic Bacteria. New York, Boston, Dordrecht, London, Moscow: Kluwer Academic Publishers; 2004. p. 1–15.
[56] Kuo FS, Chien YH, Chen CJ. Effects of light sources on growth and carotenoid content of photosynthetic bacteria *Rhodopseudomonas palustris*. Bioresour Technol 2012;113(Jun):315–8.
[57] Katsuda T, Lababpour A, Shimahara K, Katoh S. Astaxanthin production by *Haematococcus pluvialis* under illumination with LEDs. Enzyme Microb Technol 2004;35(Jul):81–6 (9).
[58] Carpenter SR, Caraco NF, Correll DL, Howarth RW, Sharpley AN, Smith VH. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol Appl 1998;8(Aug):559–68.
[59] Vance CP, Uhde-Stone C, Allan DL. Phosphorous acquisition and use: critical adaptations by plants for securing a nonrenewable resource. N Phytol 2003;157(Mar):432–47.
[60] Baturin GN. Phosphorous cycle in the ocean. Lithol Miner. Resour 2003;38 (Mar):101–19.
[61] Pittman JK, Dean AP, Osundeko O. The potential of sustainable algal biofuel production using wastewater resources. Bioresour Technol 2011;102(Jan): 17–25.
[62] Aslan S, Kapdan IK. Batch kinetics of nitrogen and phosphorus removal from synthetic wastewater by algae. Ecol Eng 2006;28(Nov):64–70.
[63] Richmond A, Cheng-Wu Z. Optimization of a flat plate glass reactor for mass production of *Nannochloropsis* sp. outdoors. J Biotechnol 2001;85(Feb): 259–269.
[64] Boeuf G, Le Bail PY. Does light have an influence on fish growth? Aquaculture 1999;177(Jul):129–52.
[65] Migaud H, Cowan M, Taylor J, Ferguson W. The effect of spectral composition and light intensity on melatonin, stress and retinal damage in post-smolt Atlantic salmon, *Salmo salar*. Aquaculture 2007;270(Sep):390–404.
[66] Villamizar N, García-Alcazar A, Sánchez-Vázquez FJ. Effect of light spectrum and photoperiod on the growth, development and survival of European sea bass (*Dicentrarchus labrax*) larvae. Aquaculture 2009; 292(July):80–6.
[67] Villamizar N, Blanco-Vives B, Migaud H, Davie A, Carboni S, Sanchez-Vazques FJ. Effects of light during early larval development of some aquacultured teleosts: a review. Aquaculture 2011;315(May):86–94.
[68] Bayarri MJ, Madrid JA, Sánchez-Vázquez FJ. Influence of light intensity, spectrum and orientation on sea bass plasma and ocular melatonin. J Pineal Res 2002;32(Jan):34–40.
[69] Vera LM, Davie A, Taylor JF, Migaud H. Differential light intensity and spectral sensitivities of Atlantic salmon, European sea bass and Atlantic cod pineal glands *ex vivo*. Gen Comp Endocrinol 2010;165(Jan):25–33.
[70] Migaud H, Cowan M, Taylor J, Ferguson HW. The effect of spectral composition and light intensity on melatonin, stress and retinal damage in post-smolt Atlantic salmon, *Salmo salar*. Aquaculture 2007;270(Sep):390–404.
[71] Pickering AD, Pottinger TG. Stress responses and disease resistance in salmonid fish: effects of chronic elevation of plasma cortisol. Fish Physiol Biochem 1989;7(June):253–8.
[72] Inada H, Arimoto T. Trends on research and development of fishing light in Japan. J Illum Eng Inst Jpn 2007;91(4):199–209.
[73] Arimoto T. Fish behaviour control by use of light. Fish Eng 1991;28:71–6.
[74] Murata M. On the distribution and the behavior under fishing lamps of young Japanese common squid, *Todarodes pacificus* Steenstrup, in the

offshore waters of northern Japan during spring and early summer. Bull Hokkaido Reg Fish Res Lab 1983;48:37–52.
[75] Arakawa H, Choi SJ, Arimoto T, Nakamura Y. Relationship between underwater irradiance and distribution of Japanese common squid under fishing lights of a squid jigging boat. Fish Sci 1998;64(4):553–7.
[76] Choi SJ. Radiation and underwater transmission characteristics of a high-luminance light-emitting diode as the light source for fishing lamps. J Kor Fish Soc 2006;39(6):480–6.
[77] An YI, Jeong HG, Jung BM. Behavioral reaction of common squid *Todarodes pacificus* to different colors of LED light. J Kor Soc Fish Tech 2009;45:135–43.
[78] An YI, Jeong HG. Catching efficiency of LED fishing lamp and behavioral reaction of common squid *Todarodes pacificus* to the shadow section of color LED light. J Kor Soc Fish Tech 2011;47(3):183–93.
[79] Jeong H, Yoo S, Lee J, An Y. The retinular responses of common squid Todarodes pacificus for energy efficient fishing lamp using LED. Renew Energy 2013;54(June):101–4.
[80] Matsushita Y, Azuno T, Yamashita Y. Fuel reduction in coastal squid jigging boats equipped with various combinations of conventional metal halide lamps and low-energy LED panels. Fish Res 2012;125–126(Aug):14–9.
[81] Migaud H, Davie A, Carboni S, Murray J, Lysaa PA, Treasurer J Effects of light on Atlantic cod (*Gadus morhua*) larvae performances: focus on spectrum. In: Hendry, CI, Van Stappen, G, Wille, M, Sorgeloos, P (Eds.), LARVI'09 – fish and shellfish larviculture symposium: Special Publication, No. 38. European Aquaculture Society, Ghent, Belgium; 2009, pp. 265–269.
[82] Downing G, Litvak MK. The effect of light intensity and spectrum on the incidence of first feeding by larval haddock. J Fish Biol 2001;59(6):1566–78.
[83] Wijgerde T, Henkemans P, Osinga R. Effects of irradiance and light spectrum on growth of the scleractinian coral *Galaxea fascicularis* – applicability of LEP and LED lighting to coral aquaculture. Aquaculture 2012;344–349 (May):188–93.
[84] Bromage N, Porter M, Randall C. The environmental regulation of maturation in farmed finfish with special reference to the role of photoperiod and melatonin. Aquaculture 2001;197(June):63–98.
[85] Bapary MAJ, Fainuulelei P, Takemura A. Environmental control of gonadal development in the tropical damselfish *Chrysiptera cyanea*. Mar Biol Res 2009;5(5):462–9.
[86] Bapary MAJ. Studies on environmental control of the reproductive activities in a tropical damselfish *Chrysiptera cyanea* [Doctoral dissertation]. Okinawa: University of the Ryukyus; 2011.
[87] Bapary MAJ, Md Amin, Takeuchi Y, Takemura A. The stimulatory effects of long wavelengths of light on the ovarian development in the tropical damselfish, *Chrysiptera cyanea*. Aquaculture 2011;314(April):188–92.
[88] Takeuchi Y, Bapary MA, Igarashi S, Imamura S, Sawada Y, Matsumoto M, et al. Molecular cloning and expression of long-wavelength-sensitive cone opsin in the brain of a tropical damselfish. Comp Biochem Physiol A Mol Integr Physiol 2011;160(Dec):486–92.
[89] Mueangdee N. Spawning detection device or the black tiger shrimp *Penaeus monodon* broodstock. Aquaculture 2013;380-383(March):21–2.
[90] Lang-Bicudo L, Fernanda De Paula Eduardo, Carlos De Paula Eduardo, Maria Zezell Denise. LED phototherapy to prevent mucositis: a case report. Photomed Laser Surg 2008;26(Dec):609–13.
[91] Sánchez-Saavedra MP, Jiménez C, Figueroa FL. Far-red light inhibits growth but promotes carotenoid accumulation in the green microalga *Dunaliella bardawil*. Physiol Plant 1996;9(Oct):419–23.
[92] Corazza A, Jacks Jorge V, Kurachi Cristina, Bagnato Vanderlei Salvador. Photobiomodulation on the angiogenesis of skin wounds in rats using different light sources. Photomed Laser Surg 2007;25(Apr):102–6.
[93] Brown CS, Schuerger AC, Sager JC. Growth and photo morphogenesis of pepper plants under red light-emitting diodes with supplemental blue or far-red lighting. J Am Soc Hortic Sci 1995;120(Sep):808–13.
[94] Johnson CF, Brown CS, Wheeler RM, Sager JC, Chapman DK, Deitzer GF. Infrared light-emitting diode radiation causes gravitropic and morphological effects in dark-grown oat seedlings. Photochem Photobiol 1996;63 (Feb):238–42.
[95] Kristina D, Paz David, Corry Jesse, Eells Janis, Wong-Riley Margaret TT, Henry Michele, et al. Clinical and experimental applications of NIR-LED photobiomodulation. Photomed Laser Surg 2006;24(Apr):121–8.
[96] Whelan HT, et al. Effect of NASA light-emitting diode irradiation on molecular changes for wound healing in diabetic mice. J Clin Laser Med Surg 2003;21(Apr):67–74.
[97] Matthijs HCP, Balke H, Van Hes UM, Kroon BMA, Mur LR, Binot RA. Application of light-emitting diodes in bioreactors: flashing light effects and energy economy in Algal culture (*Chlorella pyrenoidosa*). Biotechnol Bioeng 1996;50(Apr):98–107.
[98] Lee CG, Palsson B. High-density algal photobioreactors using light-emitting diodes. Biotechnol Bioeng 1994;44(Nov):1161–7.
[99] Ittai Neuman, Yehuda Finkelstein. Narrow-band red light phototherapy in perennial allergic rhinitis and nasal polyposis. Ann Allergy Asthma Immunol 1997;78(Apr):399–406.
[100] Yeager RL, Franzosa Jill A, Millsap Deborah S, Angell-Yeager Jennifer L, Heise Stephen S, Wakhungu Phoebe, et al. Effects of 670-nm phototherapy on development. Photomed Laser Surg 2005;23(Jun):268–72.
[101] Whelan HT, Margaret T, Wong-Riley T, Eells Janis T, VerHoeve James N, Das Rina, Jett Marti. DARPA soldier self care: rapid healing of laser eye injuries with light emitting diode technology [A]. RTO HFM Symposium [C]. Northern Mariana Islands: Trauma Technology and Emergency Medical Procedures; 2004, pp. 19–37.
[102] Miyashita Y, Kitaya Y, Kozai T. Effects of red and far-red light on the growth and morphology of Potato plantlets *in vitro*: using light emitting diode as a light source for micropropagation. Acta Hortic 1995;393:189–94.
[103] Lee Seung Yoon, You Chung Eui, Park. Mi Youn. Blue and red light combination LED phototherapy for acne vulgaris in patients with skin phototype IV. Laser Surg Med 2007;39(Feb):180–8.
[104] Wang CY, Fu CC, Liu YC. Effects of using light-emitting diodes on the cultivation of *Spirulina platensis*. Biochem Eng J 2007;37(Oct):21–5.
[105] Nhut DT, Takamura NT, Watanabe H, Tanaka M. Light emitting diodes (LEDs) as a radiation source for micro propagation of strawberry. In: Kubota, Chun, editors. Transplant Production in the 21st century: Proceedings of the International Symposium on Transplant Production in Closed System for Solving the Global Issues on Environmental Conservation, Food, Resources and Energy. New York: Springer-Verlag; LLC – November 2000, pp. 114–118. [11].
[106] Whelan HT, et al. Effect of NASA light-emitting diode irradiation on wound healing. J Clin Laser Med Surg 2001;19(December):305–14.
[107] Ró Eva, Reis Boaventura F, de la Guardia Miguel. Evaluation of a multi-commuted flow system for photometric environmental measurements. J Autom Methods Chem 2006;2006:1–9.
[108] Shin HS, Lee J, Choi CY. Effects of LED light spectra on oxidative stress and the protective role of melatonin in relation to the daily rhythm of the yellowtail clownfish, *Amphiprion clarkii*. Comp Biochem Physiol A Mol Integr Physiol 2011;160(Oct):221–8.
[109] Katsuda T, Shimahara K, Shiraishi H, Yamagami K, Ranjbar R, Katoh S. Effect of flashing light from blue light emitting diodes on cell growth and astaxanthin production of *Haematococcus pluvialis*. J Biosci Bioeng 2006;102(Nov):442–6.
[110] Mills RW, Jandt KD. Blue LEDs for curing polymer-based dental filling materials. Lasers Electro-Opt Soc Inst Electric Electron Eng Newslett 1998;12:9–10.
[111] Fujibayashi K, Ishimaru K, Takahashi N, Kohno A. Newly developed curing unit using blue light-emitting diodes. Dent Jpn 1998;34:49–53.
[112] Mills RW, Jandt KD, Ashworth SH. Dental composite depth of cure with halogen and blue light emitting diode (LED) technology. Br Dent J 1999;186 (Apr):388–91.
[113] Jandt KD, Mills RW, Blackwell GB, Ashworth SH. Depth of cure and compressive strength of dental composites cured with blue light emitting diodes (LEDs). Dent Mater 2000;16:41–7 (1);
Stahla F, Ashworth Stephen H, Jandt Klaus D, Mills Robin W. Light-emitting diode (LED) polymerisation of dental composites:flexural properties and polymerisation potentia. Biomaterials 2000;21(5):1379–85.
[114] Vreman HJ, Seidman DS, Stevenson DK. Phototherapy of jaundiced newborns using garments containing semiconductor light-emitting devices. Patent no. 6596016. United States Patent and Trademark Office Database; 2003.
[115] Schuerger AC, Brown CS, Stryjewski EC. Anatomical features of pepper plants (*Capsicum annuum* L.) grown under red light-emitting diodes supplemented with blue or far-red light. Ann Bot 1997;79(Mar):273–82.
[116] McDonald SF. Effect of visible light waves on arthritis pain: a controlled study. Int J Biosoc Research 1982;3(2):49–54.
[117] Kollias NRG, Tian WD. Phototherapy method for treatment of acne. US Patent no. 6663658, 2003.
[118] Kaidbey KH, Kligman AM. Sunburn protection by long wave ultraviolet radiation-induced pigmentation. Arch Dermatol 1978;114(Jan):46–8.
[119] Mills OH, Kligman AM. Ultraviolet phototherapy and photochemotherapy of acne vulgaris. Arch Dermatol 1978;114(Feb):221–3.
[120] Kaidbey KH, Kligman AM. The acute effects of long-wave ultraviolet radiation on human skin. J Invest Dermatol 1979;72(May):253–6.
[121] Maxim MF, Hölzle E, Hofmann C, Plewig GA. New apparatus with high radiation energy between 320–460 nm: physical description and dermatological applications. J Invest Dermatol 1981;76(Jan):42–7.